Resonant Higgs-Sector CP Violation at the LHC

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ABSTRACT

We present the general formalism for studying CP-violating phenomena in the production, mixing and decay of a coupled system of CP-violating neutral Higgs bosons at high-energy colliders. Considering the Minimal Supersymmetric Standard Model (MSSM) Higgs sector in which CP violation is radiatively induced by phases of the soft supersymmetry-breaking parameters, we apply our formalism to neutral Higgs production via $\bar{b}b$, gg and W^+W^- collisions and their subsequent decays into $\tau^+\tau^-$ pairs at the LHC. We discuss CP asymmetries in the longitudinal polarizations of $\tau^+\tau^-$ pairs based on a scenario in which all neutral Higgs bosons are nearly degenerate and the CP-violating signatures are resonantly enhanced.

1. Introduction

In the presence of non-vanishing CP phases in the soft SUSY-breaking terms, radiative corrections naturally induce a mixing between CP-odd and CP-even Higgs states [1]. The main contribution comes from stop and sbottom loops due to the large Yukawa couplings, the size of the CP-violating mixing being proportional to [2]

$$\Delta_{\tilde{f}} \equiv \frac{\Im m(A_f \, \mu)}{(m_{\tilde{f}_2}^2 - m_{\tilde{f}_1}^2)} \tag{1}$$

with f=t,b. Here the A_f 's are complex trilinear soft-breaking parameters, μ is the complex supersymmetric Higgs(ino) mass parameter, and the $m_{\tilde{f}_i}$, i=1,2, are the squark mass eigenvalues. Even though the mixing is loop-suppressed, its effects can be sizable even for small values of $\Im(A_f \mu)$, especially when two or more neutral Higgs bosons are nearly degenerate [3].

In the presence of this non-trivial mixing with non-vanishing CP phases, the neutral Higgs bosons do not have to carry any definite CP parity and the mixing among them is described by the orthogonal 3×3 matrix instead of a 2×2 one and, accordingly, the couplings of the Higgs bosons to the SM and SUSY particles are greatly modified. The most prominent example is the Higgs-boson coupling to a pair of vector bosons, which is responsible for the production of Higgs bosons at e^+e^- colliders. In fact, the lightest Higgs boson H_1 lighter than 50 GeV could have been undetected at LEP2 for intermediate values of $\tan \beta$ [4].

Recently a computational tool called CPsuperH [5] has been developed for Higgs phenomenology in the MSSM with explicit CP violation. This code calculates the Higgs boson pole masses [6], Higgs-boson mixing matrix, all the couplings of Higgs bosons to the SM and SUSY particles, and the decay widths and branching fractions of the neutral

and charged Higgs bosons [7].

2. Higgs-boson propagator matrix

In a situation where two or more neutral Higgs bosons are simultaneously involved in a process due to their mass differences comparable to their decay widths, the full 3×3 Higgs boson propagator matrix $D(\hat{s})$ should be considered ^a:

$$D(\hat{s}) = \hat{s} \begin{pmatrix} \hat{s} - M_{H_1}^2 + i \Im \hat{\Pi}_{11}(\hat{s}) & i \Im \hat{\Pi}_{12}(\hat{s}) & i \Im \hat{\Pi}_{13}(\hat{s}) \\ i \Im \hat{\Pi}_{21}(\hat{s}) & \hat{s} - M_{H_2}^2 + i \Im \hat{\Pi}_{22}(\hat{s}) & i \Im \hat{\Pi}_{23}(\hat{s}) \\ i \Im \hat{\Pi}_{31}(\hat{s}) & i \Im \hat{\Pi}_{32}(\hat{s}) & \hat{s} - M_{H_3}^2 + i \Im \hat{\Pi}_{33}(\hat{s}) \end{pmatrix}^{-1},$$

$$(2)$$

where M_{H_i} 's are Higgs-boson pole masses and for the absorptive parts of the Higgs-boson propagator matrix, $i\Im \widehat{\Pi}_{ij}(\hat{s})$, we have included contributions from loops of fermions (third generation leptons and quarks, charginos, and neutralinos), vector bosons, associated pairs of Higgs and vector bosons, Higgs-boson pairs, and sfermions.

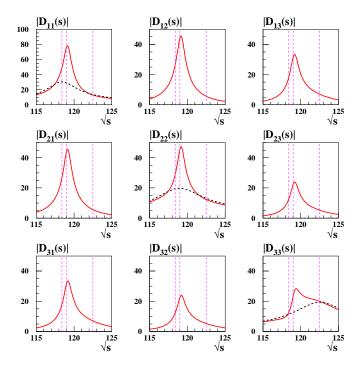


Figure 1: The absolute value of each component of the Higgs-boson propagator matrix $|D_{ij}(s)|$ with (red solid lines) and without (black dashed lines) including off-diagonal absorptive parts in the three-way mixing scenario with $\Phi_A = -\Phi_3 = 90^\circ$. Three Higgs-boson pole masses are presented with vertical lines.

In Fig. 1, we show the absolute value of each component of the Higgs-boson propagator matrix, $|D_{ij}(s)|$, in the so-called three-way mixing scenario, which is characterized by a

^aHere we neglect the small off-diagonal absorptive parts between Goldstone and Higgs bosons.

large value of $\tan \beta = 50$ and small $M_{H^{\pm}}^{\text{pole}} = 155$ GeV with $\Phi_A = -\Phi_3 = 90^{\circ}$ [3]; $\Phi_A \equiv \arg(A_t \mu) = \arg(A_b \mu)$ and $\Phi_3 \equiv \arg(M_3 \mu)$ with M_3 the gluino mass parameter. We observe the inclusion of the off-diagonal absorptive parts significantly modifies the Higgs-boson propagators: the peak positions could be different from pole-mass positions and the off-diagonal transition propagators can be sizable and should not be neglected.

3. At the LHC

We have considered three main neutral Higgs-boson production mechanisms at the LHC and the significant mixing among Higgs bosons before decaying into τ leptons:

• b-quark fusion : $pp(b\bar{b}) \to H_{i\to j}X \to \tau^+\tau^-X$

• gluon fusion : $pp(gg) \to H_{i \to j} X \to \tau^+ \tau^- X$

• W-boson fusion: $pp(W^+W^-) \to H_{i\to j}X \to \tau^+\tau^-X$

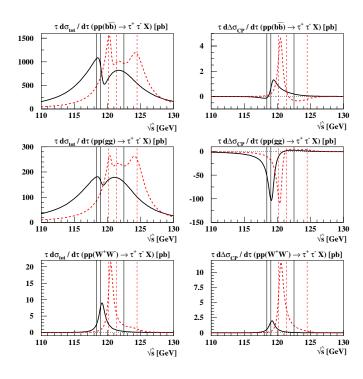


Figure 2: The differential total and CP-violating cross sections, $\tau \frac{d\sigma_{\text{tot}}}{d\tau}$ and $\tau \frac{d\Delta\sigma_{\text{CP}}}{d\tau}$, as functions of the tau-lepton invariant mass $\sqrt{\hat{s}} = \sqrt{(p_{\tau^+} + p_{\tau^-})^2}$ in the three-way mixing scenario with $(\Phi_A, \Phi_3) = (90^\circ, -90^\circ)$ (black solid lines) and $(\Phi_A, \Phi_3) = (90^\circ, -10^\circ)$ (red dashed lines). The vertical lines show the positions of three Higgs-boson pole masses in each case. The kinematic parameter $\tau = \hat{s}/s$ with s the hadron-collider energy squared.

In Fig. 2, we show the differential total and CP-violating cross sections defined by:

$$\sigma_{\text{tot}} \equiv \sigma(pp \to \tau_R^+ \tau_R^- X) + \sigma(pp \to \tau_L^+ \tau_L^- X),$$

$$\Delta\sigma_{\text{CP}} \equiv \sigma(pp \to \tau_R^+ \tau_R^- X) - \sigma(pp \to \tau_L^+ \tau_L^- X).$$
(3)

It is indispensable to measure the longitudinal polarizations of tau leptons to construct the CP-violating cross section $\Delta\sigma_{\rm CP}$ which is non-vanishing only in the presences of non-trivial CP phases and the absorptive parts in the Higgs-boson propagators or their vertices.

We observe that the b-quark fusion is the dominant production mechanism [8] and the total cross section is at least five times larger than the gluon fusion cross section. This large cross-section reduces the would-be large CP asymmetry in the gluon-fusion channel below 1% level after combining b-quark and gluon fusion channels. The reason is that in the scenario under consideration b-quark rescattering effects dominate the resonant transition amplitude, leading to a strong suppression of CP violation [3]. We also note that the peak positions don't exactly coincide with the Higgs-boson pole-mass positions and the resonance shape strongly depends on the production channels.

Though the WW-fusion cross section is the smallest one, this process can be discriminated experimentally from b-quark and gluon fusion ones and can be very promising for detecting Higgs sector CP violation at the LHC. We find that the CP asymmetry given by the ratio $\sigma_{\rm tot}/\Delta\sigma_{\rm CP}$ is large over wide range of CP phases. Especially, it can be easily larger than 30 % even for small CP phases and reach to 80 % when $\Phi_3 = -70^{\circ}$ as shown in Figs. 8–11 of Ref. [3].

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5. References

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